

Searches for New Physics in Top Decays at D0

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Abstract

The Tevatron proton-antiproton collider at Fermilab with its centre of mass energy of 1.96 TeV allows for pair production of top quarks and the study of top quark decay properties. This report reflects the current status of measurements of the W boson helicity in top quark decays and the ratio of top quark branching fractions as well as searches for neutral current top quark decays and pair production of fourth generation t' quarks, performed by the D0 Collaboration utilising datasets of up to 5.4 fb^{-1} .

1 Introduction

With a mass of $m_t = 173.2 \pm 0.9 \text{ GeV}$ [1], the top quark is the most massive fundamental particle known to date. Top quarks are mainly produced in pairs via the strong interaction, with a cross section of $\sigma_{t\bar{t}} = 7.3_{-0.6}^{+0.5} \text{ pb}$ [2] in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. In the framework of the Standard Model (SM), top quarks decay almost exclusively into W bosons and b quarks. Consequently, top quark pair events contain a b and a \bar{b} quark from the $t\bar{t}$ decay, and the remaining final state to be observed depends on the decay mode of the two W bosons.

The analyses presented here focus on two signatures: (i) events where both W bosons decay leptonically, resulting in a final state containing two isolated high- p_T leptons, missing transverse energy \cancel{E}_T corresponding to the two neutrinos and two (b -) jets (*dilepton* events) and (ii) events where one W boson decays leptonically, the other one hadronically, resulting in one isolated high- p_T lepton, \cancel{E}_T and four jets (*lepton + jets* events). As leptons only electrons and muons are considered in these analysis channels, including those from leptonic τ decays.

2 Searches for New Physics in Top Quark Pair Decays

Measurement of the W Boson Helicity

Top quark decays in the SM proceed via the left-handed charged current weak interaction, which results in a suppression of right-handed W bosons. The expected fractions of the three possible helicity states of the W boson are: longitudinal fraction $f_0 \approx 69\%$, left-handed fraction $f_- \approx 31\%$ and right-handed fraction $f_+ \approx 10^{-3}$ [3]. The W boson helicity is reflected in the angular distribution $\cos\theta^*$ of its decay products, with θ^* being the angle of the down-type decay products of the W boson (charged lepton, d - or s -quark) in the W boson rest frame relative to the top quark direction. Any observation of f_+ at the percent level would signal new physics beyond the SM.

D0 measures the W boson helicity using a dataset corresponding to an integrated luminosity of 5.4 fb^{-1} , using both lepton + jets and dilepton final states of $t\bar{t}$ decays [4]. Since the measurement is still expected to be limited by sample statistics, the event selection in each channel is optimised for $t\bar{t}$ acceptance, using multivariate likelihood discriminants based on event topology and object kinematics. In the lepton + jets channel, the event kinematics is obtained from the best kinematic fit to the $t\bar{t}$ event hypothesis, which enables the calculation of $\cos\theta^*$ for the leptonic W boson decay. The hadronic W boson decay is utilised as well to evaluate $|\cos\theta^*|$, which does not permit discrimination between right- and left-handed W bosons, but still adds information to further constrain f_0 . In the dilepton events, $m_t = 172.5 \text{ GeV}$ is assumed and $\cos\theta^*$ is obtained for each top quark as the average over all possible solutions of the event kinematics, taking lepton and jet energy resolutions into account by varying the energies within their uncertainties.

By comparing the observed angular distributions in data with templates of background and $t\bar{t}$ signal with varying W boson helicity admixtures, f_0 and f_+ can be extracted in a simultaneous fit ($f_- = 1 - f_+ - f_0$). This model-independent fit yields:

$$f_0 = 0.669 \pm 0.078 (\text{stat.}) \pm 0.065 (\text{syst.}), \quad f_+ = 0.023 \pm 0.041 (\text{stat.}) \pm 0.034 (\text{syst.}),$$

in excellent agreement with the SM expectation.

Search for Neutral Current Top Decays

Transitions between quarks of different flavour but identical charge (flavour changing neutral currents, FCNC) are forbidden at lowest order and heavily suppressed at higher orders in the SM. The decay $t \rightarrow Zq$ (with $q = u, c$) thus is expected to occur with a branching fraction of $\mathcal{O}(10^{-14})$ [5], well out of reach of experimental sensitivity. Any observation of FCNC decays would indicate physics beyond the SM.

D0 performs a search for $t\bar{t} \rightarrow WbZq + X$ decays based on a dataset corresponding to an integrated luminosity of 4.1 fb^{-1} , using the trilepton final state

$\ell'\nu\ell\bar{\ell}$ + jets for the first time in this kind of search [6]. This signature benefits from low background contributions, but also suffers from limited statistics. After a basic preselection reflecting the decay signature, signal and background (mainly diboson and V + jets production) are separated using distributions of jet multiplicity, scalar sum of the transverse momenta of leptons, jets and \cancel{E}_T (H_T), and the reconstructed top quark mass from the $t \rightarrow Zq$ decay.

All observed distributions are consistent with the SM background contributions, and consequently 95% C.L. limits on FCNC decays of $t\bar{t}$ are derived:

$$\mathcal{B}(t \rightarrow Zq) < 3.2\%,$$

with an expected limit of 3.8 %. This is currently the world's best limit on $\mathcal{B}(t \rightarrow Zq)$.

Search for Fourth Generation t' Quark Pair Production

While a fourth generation of fermions with a light neutrino ($m_\nu < m_Z/2$) has been ruled out by electroweak precision data, the constraints on a fourth generation are much relaxed if the neutrino is sufficiently heavy. For example, a fourth generation t' quark mass of 400 GeV can be compatible with electroweak precision measurements, and the mass splitting relative to the corresponding b' quark is constrained to be small, leading to a preferred decay $t' \rightarrow Wq$ ($q = d, s, b$) [7].

Based on a dataset with an integrated luminosity of 5.3 fb^{-1} , D0 searches for pair production of fourth generation up-type quarks ($t'\bar{t}'$), assuming the intrinsic t' width is smaller than the detector resolution and the decay always proceeds via Wq [8]. Consequently, the $t'\bar{t}'$ decay chain is identical to that of the top quark pair production, and the lepton + jets final state is used for the search with no b -jet identification applied. To separate the signal from SM background processes, the observed events are compared with signal and background contributions in two-dimensional histograms of the scalar sum of lepton- p_T , jet- p_T and \cancel{E}_T (H_T) versus t' mass m_{fit} from a kinematic fit to the event hypothesis. Based on the observed agreement between data and the SM contributions, 95% C.L. limits are derived on the $t'\bar{t}'$ production cross section as a function of $m_{t'}$.

While in the e + jets channel reasonable agreement between data and simulation is observed, in the μ + jets channel an excess of data over SM background is visible around $m_{fit} = 325 \text{ GeV}$. However, the data are best described with a $t'\bar{t}'$ production cross section 3.2 ± 1.1 times the predicted cross section for $m_{t'} = 325 \text{ GeV}$. The probability of observing an excess of at least this size from the SM background processes alone corresponds to 2.5 standard deviations. Combining the observations from both channels, $t'\bar{t}'$ production can be excluded at 95% C.L. for

$$m_{t'} < 285 \text{ GeV},$$

with an expected exclusion below 320 GeV.

Measurement of $\mathcal{B}(t \rightarrow Wb)/\mathcal{B}(t \rightarrow Wq)$

The ratio of top quark branching fractions R can be expressed via CKM matrix elements as $R = \mathcal{B}(t \rightarrow Wb) / \sum_{q=d,s,b} \mathcal{B}(t \rightarrow Wq) = |V_{tb}|^2 / \sum_{q=d,s,b} |V_{tq}|^2$ and provides therefore a measure of the relative size of $|V_{tb}|$ compared to $|V_{td}|$ and $|V_{ts}|$. Within the framework of the SM, assuming a unitary 3×3 CKM matrix and insignificance of non- W boson decay modes of the top quark, the above expression simplifies to $R = |V_{tb}|^2$ and R is strongly constrained from global CKM fits: $R = 0.99830^{+0.00006}_{-0.00009}$ [9]. Deviations of R from unity could for example be a sign for the presence of a fourth heavy quark generation or non-SM top quark decay modes.

D0 measures R in a dataset corresponding to an integrated luminosity of 5.4 fb^{-1} , using both the lepton + jets and dilepton $t\bar{t}$ decay channels [10]. In the lepton + jets channels, the number of identified b -jets (0, 1, ≥ 2) is used together with a multivariate kinematic discriminant to separate the $t\bar{t}$ signal from background in subsamples dominated by background in order to extract R simultaneously with the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$, yielding $R = 0.95 \pm 0.07$ (stat. + syst.) and $\sigma_{t\bar{t}} = 7.90^{+0.79}_{-0.67}$ (stat. + syst.) pb. In the dilepton channels, the lowest value of a neural network b -jet identification algorithm applied to the leading jets in each event is used as a discriminant, yielding $R = 0.86 \pm 0.05$ (stat. + syst.) and $\sigma_{t\bar{t}} = 8.19^{+1.06}_{-0.92}$ (stat. + syst.) pb. These measurements allow the extraction of $\sigma_{t\bar{t}}$ without assuming $\mathcal{B}(t \rightarrow Wb) = 1$ as usually done in $t\bar{t}$ cross section measurements. Combining both measurements yields:

$$R = 0.90 \pm 0.04 \text{ (stat. + syst.) and } \sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57} \text{ (stat. + syst.) pb.}$$

The cross section measurement is in good agreement with the SM expectation, and the R measurement is within approximately 2.5 standard deviations of the SM expectation, being the most precise measurement to date.

3 Summary

D0 is pursuing a wealth of top quark physics analyses that probe the validity of the SM, a few of which are presented in this report. So far, no evidence for new physics phenomena has been found in top quark decays. The search continues now both at the Tevatron and the LHC, and will include updates to the analyses presented here.

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